Training Powered Wheelchair Manoeuvres in Mixed Reality

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***Abstract*—We describe a mixed reality environment that has been designed as an aid for training driving skills for a powered wheelchair. Our motivation is to provide an improvement on a previous virtual reality wheelchair driving simulator, with a particular aim to remove any cybersickness effects. The results of a validation test are presented that involved 35 able bodied volunteers divided into three groups: mixed reality trained, virtual reality trained, and a control group. No significant differences in improvement was found between the groups but there is a notable trend that both the mixed reality and virtual reality groups improved more than the control group. Whereas the virtual reality group experienced discomfort (as measured using a simulator sickness questionnaire), the mixed reality group experienced no side effects.**

***Index Terms*—Mixed Reality, Training, Powered Wheelchair**

I. Introduction

There are many people who need to use a powered wheelchair to aid in their mobility and the powered wheelchair market in the United States alone is expected to reach $3.9 billion during this year. When a person is referred to their local Wheelchair Service they will be assessed by an occupational therapist. However, there is no common assessment standard and most Wheelchair Services have developed their own protocols. When new to a wheelchair collisions will be frequent resulting in potential injuries, as well as damage to furniture, walls, doors, etc. Training opportunities in driving a wheelchair are limited. Emerging technologies such as Virtual Reality (VR) offer a training medium that could be exploited, and there have been several studies published (e.g. [1], [2], [3]). We have also produced a VR system based on the new generation of VR head mounted displays, and our initial validation study produced promising results [4]. The user is immersed into a series of different environments in which they can practice driving a virtual powered wheelchair. The main drawback of our system has been the cybersickness effects that many users have experienced. We are currently exploring different strategies for alleviating this problem and one possibility is to use a Mixed Reality (MR) environment. This paper describes the MR system that we have developed and the initial validation study carried out to test its effectiveness.

The structure of the paper is as follows: Section II provides a review of MR training related to wheelchair experiences. Section III describes Wheelchair-MR, the system that was developed to explore the above hypothesis. Section IV presents the validation study on the use of Wheelchair-MR with able-bodied volunteers and discusses its results. Finally the paper ends with the conclusions from the study and a discussion of future work.

II. Related Work

In our review of the recent developments and trends of MR in medical application areas [5], use of the technology in rehabilitation and training are identified as areas of strong growth. Rehabilitation is probably the most mature of the medical application areas currently using MR, and will continue to flourish as more home use deployment becomes possible. Very little that has been published related specifically to wheelchair users, however.

Mobile Augmented Reality (AR) was used by de Oliveira *et al.* [6] to aid in the indoor navigation of a building. They calculated routes free of potential hazards for wheelchair users and then used fiducial markers to provide directional arrows via their mobile AR interface. A small test study was carried out which indicated the potential of their approach. The participants had to view the augmented world through the camera on a hand held mobile device, which typically requires them to be stationary when looking at the markers from their wheelchair. The use of fiducial markers will be replaced in future work.

Work has also been carried out to help automatically manoeuvre a wheelchair when used in a confined space [7]. They use the simultaneous localization and mapping (SLAM) algorithm to obtain the environment and robot information that can be used for path planning. SLAM is commonly used today for marker-less mixed reality applications.

Few examples are currently available that demonstrate the use of mixed reality, both immersive and non-immersive, in the training of wheelchair usage. One such example is a serious games applications created by Secoli *et al* [8]. They created a MR application that used a wheelchair as an input mechanism for a range of games. The wheelchair would sit on a set of rollers that would provide input to the games, and the systems display was projected on the floor of the room. Each game was designed to teach the user a specific aspect of wheelchair use. For example, one of the games was a baseball game designed to teach the user the cause and effect of using the joystick on a powered wheelchair, and another was designed to teach forward and backwards control using a ”pong” style game.

Another example is one was a telerehabilitation application [9]. They used a small electronic vehicle with a camera attached to simulate a wheelchair moving through an environment containing markers that could be augmented with virtual objects. The wheelchair commands can be issued remotely by either the patient or a health professional.

Nobody is yet exploiting the new generation of headsets such as the Microsoft Hololens (Microsoft Inc., Redmond, WA) or Meta glasses (Meta, San Mateo, CA) to provide a more intuitive marker-less mixed reality interface for wheelchair users on the move. This is what we have implemented in our system.

III. Methods and Tools

We have developed a MR environment for a powered wheelchair user to drive through. It uses an empty space in the real world, but the user sees virtual obstacles that they have to manoeuvre around - see Fig. 1. Visual and audio cues are given if they collide with an object but no physical damage can be done. The system can be used with any wheelchair, including all classes and configurations of both powered and manual wheelchairs. In Fig. 1 a rear wheel drive Scandinavian Mobility wheelchair is being used.

Fig. 1: The Wheelchair-MR System in use. The user is wearing a Microsoft Hololens and is driving a powered wheelchair through an empty space in the real world. However, virtual objects (tables and chairs) are present and the user must manoeuvre around them.

A. Hardware Components

Over the past few years, affordable VR Head Mounted Displays (HMDs) have become available. These devices are extremely popular and have a lot of potential. Unfortunately, an inherent issue with them is cybersickness. Similar to motion-sickness, it occurs when a user perceives motion but does not experience it, which disrupts the vestibulo-ocular reflex. This can make the user feel disorientated, nauseous, and dizzy. Mixed Reality head mounted displays are not susceptible to the same problem as you still see and interact in the real world and you have to physically move around. These headsets offer a natural way of viewing virtual objects and information overlaid on the real world environment. The Microsoft Hololens was chosen for this study as it is tetherless and does not need to be connected to an external computer. It contains a sophisticated array of sensors, including ”environment understanding”, depth, and high definition cameras. These sensors allow the Hololens to scan the environment that it is currently in. The 3D model generated from the scan is then used by the device to position itself and objects within the environment. A limitation is its relatively small field of view, roughly 35° that it supports.

B. Software Implementation

Wheelchair-MR was developed using the Unity 3D games engine (Unity Technologies, San Francisco, CA) and Mixed Reality Toolkit developed by Microsoft for their VR/MR devices. The system runs directly on the Microsoft Hololens device and no external devices, such as computers or tracking sensors, are required.

1) User Interface: As the trainee starts the application, they place a User Interface (UI) panel, via the headset and using the airtap gesture, at a convenient position in the real world. This gives them access to the controls for the environment. The user interface is split into separate sections. Other debug information can be supplied as necessary. Fig. 2 shows the scenarios that can be selected. The left hand panel contains collision metrics for the user. This includes a breakdown of which parts of the chair that the user has hit objects with and how many times per area. These metrics can help the user to improve their driving skill by informing them where they are having the most collisions so that they can adapt accordingly. A loading animation (not visible in the figure) is also present to indicate that a task, such as loading a scenario or saved room, is running.

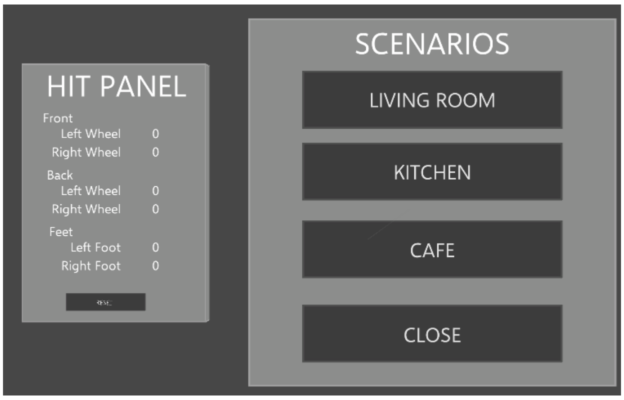
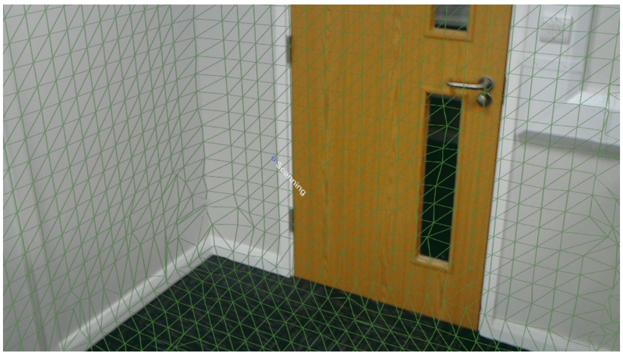


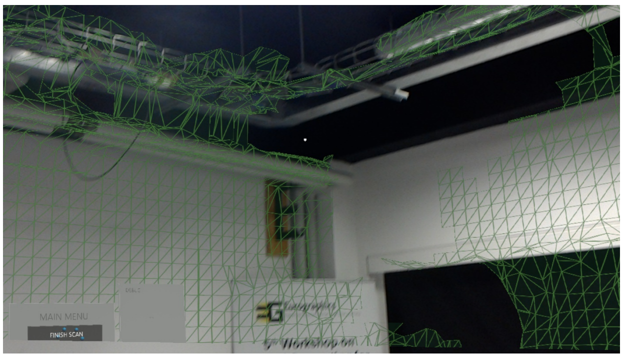
Fig. 2: Scenario Menu allowing the user to select specific scenarios

2) Spatial Understanding: The Hololens’ spatial mapping and understanding capabilities allow it to scan the trainee’s current environment. When the trainee starts the scanning process via the UI, the input from the camera array is converted into mesh data and stored as a grid of 8cm sized voxel cubes. This data is then placed based on the information obtained from the depth camera and the initial orientation of the device, slowly rebuilding a seamless representation of the trainee's environment within the application. Once the trainee finalizes the scan, the system fills in any missing data that wasn't captured during the scanning phase based on its best estimation.

The mesh environment that is generated from the scanning stage is then used by the system to "understand" the semantics of the environment. This means that the system steps through each section of the mesh and tags it with a surface type based on what the system thinks it is. The options include Ceiling, Interior Wall, Exterior Wall, Floor, Platform (anywhere between floor and ceiling), Other or Invalid. This "understanding" of the environment allows the system to then place objects according to a set of rules such as on a wall, surface, in mid-air, near a point, or away from walls or other objects, and other constraints defined by the developer. The system uses the rules to initially find a suitable location to place an object, then uses the constraints to further refine the placement. This allows the Hololens to accurately place the objects in a way that would fit in a real world context. Fig. 3 shows a virtual representation of the 3D environment as a mesh, superimposed onto an actual room.



(a)



(b)

Fig. 3: Two views of the mesh generated by the Hololens' spatial mapping capability

3) Chair Simulation: As this is a Mixed Reality application, the wheelchair does not need to be rendered within the environment. However, to allow the wheelchair to interact with the virtual objects, a group of physics colliders are used to match the generic shape of a wheelchair - see Fig. 4. These are mapped onto the current position of the real chair throughout. The colliders are used within Unity for collision detection, here they tell us when the wheelchair collides with the virtual furniture by updating the UI and generating a short noise that resembles something hitting an object.

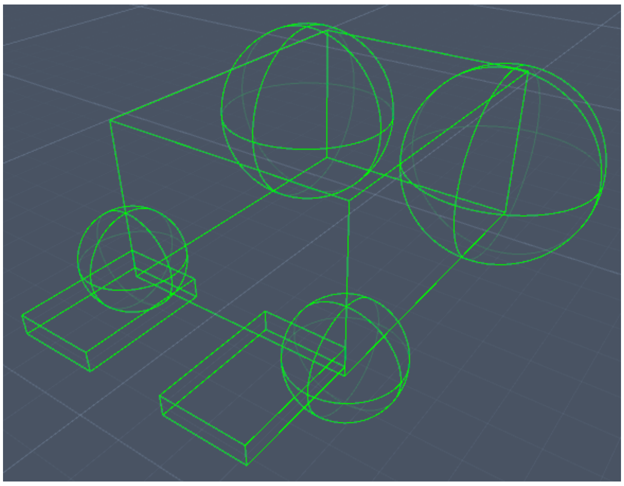


Fig. 4: The physics colliders used to represent the chair

4) Training Task: The purpose of the application is to allow a trainee to practice manoeuvring a powered wheelchair within a safe environment. Three scenarios are available; a living room, kitchen, and café. Each scenario has several different objects associated with it that are placed within the environment based on predefined rules and constraints. These objects can also be manually repositioned using the Hololens' gesture interface. A future version will allow the trainee to re-create the furniture as laid out in their own homes.

IV. Validation Study

A. Experimental Design

A validation study was designed to provide feedback on whether using Wheelchair-MR had any impact on training when compared with our VR system, and a control group. Thirty-five able-bodied volunteers participated in the study, consisting of 9 Females and 26 Males. The ages of the participants ranged from 18 to 70 years old. All participants had their average reaction time recorded using an online tool called Human Benchmark and achieved an average around 0.4 ± 0.04 seconds, which is well within the acceptable range recommended for safe use of a powered wheelchair. The participants were randomly assigned to one of the three groups, while maintaining an even distribution between them. The groups consisted of a Control group who would just read pamphlets with driving hints for a powered wheelchair, a VR group who trained using our VR training simulator, and a MR group who trained using the MR training environment (See Table I).

TABLE I: Group-per-session Allocation

	Control	VR	MR
Obstacle Course	✓	✓	✓
Training (VR)		✓	
Training (MR)			✓
Obstacle Course	✓	✓	✓

To assess each participants baseline wheelchair driving skills, they were initially required to complete a series of tasks presented as a timed obstacle course using a Spectra XTR2 with rear-wheel drive. The time taken by each participant was recorded as well as the number of times they hit a cone or left the bounds of the course. The obstacle course consisted of four stages (see Fig. 5 and Fig. 6):

1) To manouevre through a narrow doorway - represented by a set of cones - and stop on the other side.
2) To drive in a circular path, stopping at a specified point.
3) To complete a slalom course through seven cones, placed 1.5m apart.
4) To reverse park the chair in a small area marked out by cones.

A time penalty worth one second was added for each cone hit or unwanted exit that the participant incurred.

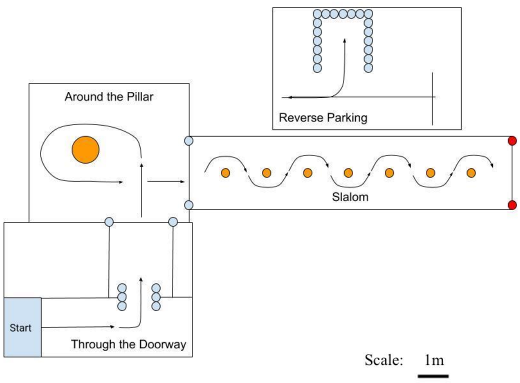


Fig. 5: Design view of the Layout of the Obstacle Course

The participants were then randomly assigned to one of the three groups through a random selection process and completed their training activity:

1) The VR group trained using Wheelchair-VR [4] with the Oculus Rift HMD. The participants were sat at a desk, with the controller in their hand to control the virtual wheelchair. They were required to complete two different scenarios that involved driving the virtual wheelchair through a maze and through doorways. Participants were allowed to complete the training in their own time, but no-one took more than 10 minutes to complete the scenarios.
2) The MR group were taken to a nearby empty area where they used the Wheelchair-MR system with the café scenario pre-loaded. They were asked to navigate their way through the area, making their way from one end to the other whilst avoiding the virtual tables and chairs that were placed within the environment. Participants were allowed a short period to adjust to the MR headset before given 5 minutes to carry out their training. They used the Scandinavian Mobility rear-wheel chair for this task.
3) The control group were asked to read through two separate guides about using a powered wheelchair safely [10], [11].

Fig. 6: The Slalom Section of the Obstacle Course

The VR and MR groups were also asked to complete a simulator sickness questionnaire (SSQ) so that any occurrence of cybersickness could be recorded [12]. If the participants from either group felt ill at any stage while using the headsets, there were told to remove them immediately.

A second run of the obstacle course was then completed. The majority of participants improved on this run. We were interested in any difference in the rate of improvement between the three groups.

B. Results

A one-way analysis of variance (ANOVA) was carried out on the times to complete each task from the first run of the course. No significant difference was found for the circular path, slalom and reverse parking tasks. However, a significant difference ($p = 0.043$) was found for the first run of the doorway task. We therefore excluded this task from the improvement analysis that follows.

An improvement parameter was defined as the difference between the scores from each participants first and second runs of the course, divided by the maximum value from that participants two runs. This normalized value is expressed as a percentage, with the sign denoting whether the participant got better or worse on their second attempt. The box plot in Fig. 7 summarizes this improvement for the three groups over the course, excluding the doorway task. The median values, represented by the thick black horizontal line, for both MR (14%) and VR (16.7%) are clearly higher than that of the control group (10.2%), and in general the data in the first and third quartiles have higher improvement values. This suggests that there was more improvement from those two groups.

One-way ANOVAS were next calculated to compare the improvement between the three groups. Not including the outlier in the Control group (see Fig. 7), the overall improvement scores for the course gave a p-value of 0.399. This is not significant.

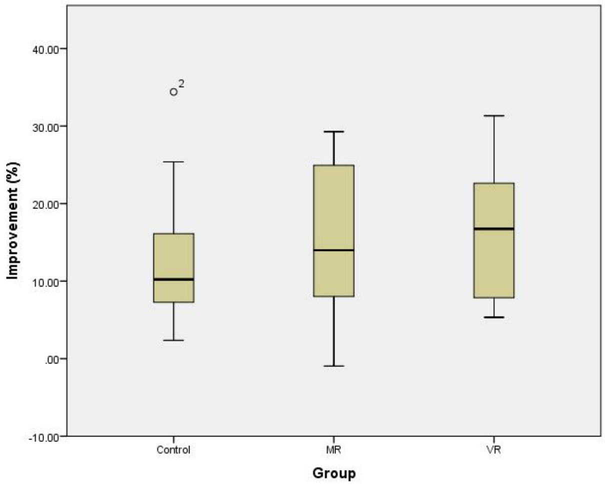


Fig. 7: The overall improvement across the entire course. The outlier is marked with a circle

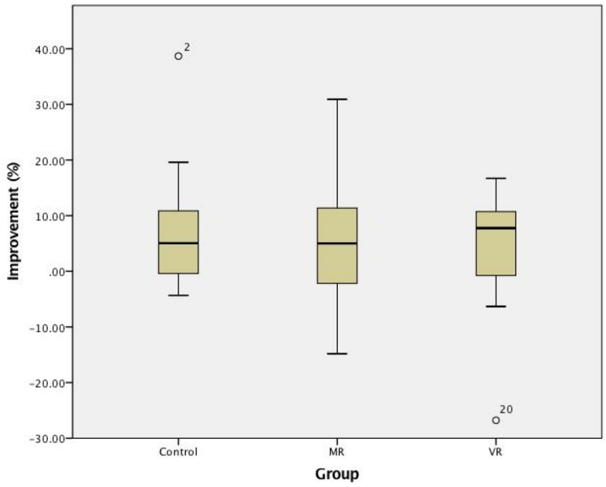


Fig. 8: The improvement for a circular path around a pillar

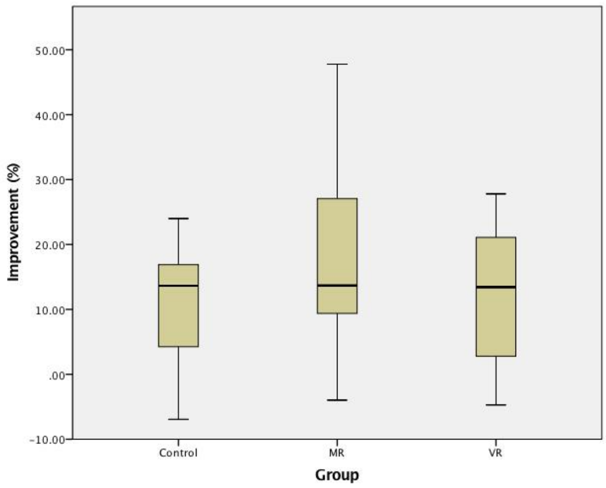


Fig. 9: The improvement for the slalom

Analysing each of the tasks individually, when navigating around a pillar, the median improvement values for the Control, MR, and VR groups are 5%, 5%, and 7.7% respectively. Excluding the two outliers indicated in Fig. 8, a p-value of 0.930 is obtained from a one-way ANOVA of the improvement parameter for this task. There is no significant difference between any of the three groups and the distribution of data in the first and third quartiles is similar.

In the slalom task, the median improvement values for the Control, MR, and VR groups are 13.6%, 13.7%, and 13.4% respectively. However, the MR group shows a greater mean overall improvement, with an increase of 17% compared to control's 11% and VR's 12%. The box-plots in Fig. 9 summarize this improvement. A one-way ANOVA generates a p-value of 0.359 for this task.

In the final task, reversing into a small space, the median improvement values for the Control, MR, and VR groups are 14.5%, 18.6%, and 31% respectively - see Fig. 10. Although the VR group shows a trend for more improvement, a one-way ANOVA (without the outliers included) gives a p-value of 0.662 so there is no significant difference between the groups.

1) Simulator Sickness Questionnaire: The VR and MR groups completed the SSQ devised by Kennedy *et al.* [12] before and after their respective training sessions. The score for each of the three symptom clusters; Nausea (N), Oculo-Motor (O), and Disorientation (D) were calculated, along with the Total Severity (TS). The results for both groups are summarized in Table II for pre-training and Table III for post-training.

Table IV shows the score ranges for each symptom level (*none*, *slight*, *moderate*, *severe*), across the symptom clusters. Each level is calculated using the sum of the scores for each symptom, each with a value between 0 (*none*) and 3 (*severe*), and multiplying that sum by the coefficient for the cluster. For example, if a person scored moderate on all symptoms of disorientation, the calculation is $(7x2)x13.92 = 194.88$,

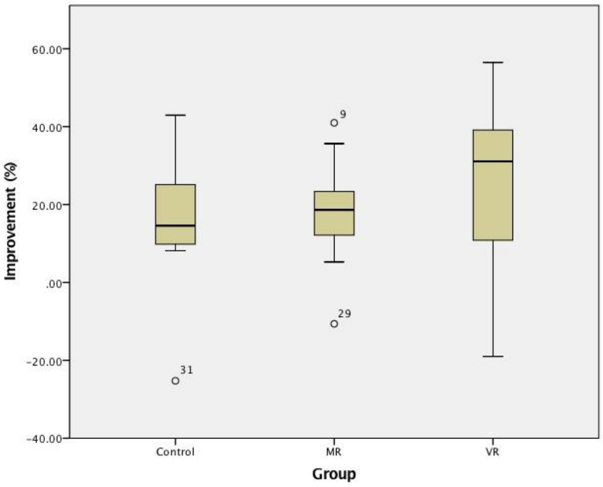


Fig. 10: The improvement for performing a reverse parking manoeuvre

where is 7 the number of symptoms in the cluster, 2 is the integer value of the moderate symptom level, and 13.92 is the coefficient for that cluster - refer to [12] for more details.

In the VR group, the average score before training showed slight levels of discomfort across all three of the symptom clusters, although several participants did experience severe discomfort for certain symptoms in areas like stomach awareness and eye strain. After their training sessions, most participants in the VR group showed increased levels of discomfort, with two noting severe discomfort in at least one symptom. One participant in particular could only use the VR simulator for a short period of time and reported moderate levels of nausea after several attempts at using the VR simulator.

The MR group also demonstrated slight levels of discomfort before and after training, but the scores after training were much lower across all three symptom clusters than that of the VR group. Some of the participants in the MR group also stated that using the MR simulator actually made them feel better after their training period. This is reflected in the results, seen in Table III, with the average scores post-training decreasing by over half in all symptom clusters.

TABLE II: SSQ - Pre-Training Scores

	Nausea		*Oculomotor*		*Disorientation*		*TS*	
Group	VR	MR	VR	MR	VR	MR	VR	MR
Mean	8.8	4.4	6.3	8.8	11.6	10.4	4.9	4.5
SD	14.9	9.5	7.8	15.8	20.4	24.6	7.8	9.5
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	47.7	28.6	22.7	45.5	69.6	69.6	26.7	25.7

TABLE III: SSQ - Post-Training Scores

	Nausea		*Oculomotor*		*Disorientation*		*TS*	
Group	VR	MR	VR	MR	VR	MR	VR	MR
Mean	47.7	2.2	27.8	3.5	67.3	3.2	26.7	1.6
SD	39.9	5.7	22.5	7.6	64.7	12.1	23.6	4.4
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	104.9	19.1	75.8	22.7	222.7	41.8	79.8	15.2

TABLE IV: SSQ - Reference Scores

	Nausea	*Oculomotor*	*Disorientation*	*Total Severity*
None	0	0	0	0
Slight	66.8	53.1	97.4	40.2
Moderate	133.6	106.1	194.9	80.4
Severe	200.3	159.2	292.3	120.5

An Independent Samples T-Test was performed on the difference between each symptom cluster before and after training for the VR and MR groups. The results of the analysis showed that there was a significant difference between the groups for each of the clusters. For Nausea, the VR and MR conditions produced a value of $t(22) = 3.442$, $p = 0.002$. In Ocular-motor, VR and MR conditions produced values of $t(22) = 3.915$, $p = 0.001$. In Disorientation, VR and MR conditions produced values of $t(22) = 3.317$, $p = 0.003$, and Total Severity, VR and MR conditions produced values of $t(22) = 3.616$, $p = 0.002$. These results suggest that the participants in the MR group displayed significantly reduced effects of cybersickness when compared the participants from the VR group. The means and standard deviations are reported in Table V.

TABLE V: T-Test Data

	Group	*Mean*	*Standard Deviation*
Nausea	VR	38.96	40.36
	MR	-2.89	10.07
Ocular-Motor	VR	27.16	25.54
	MR	-5.05	12.66
Disorientation	VR	55.68	62.25
	MR	-6.96	20.13
Total Severity	VR	22.63	23.08
	MR	-2.79	7.73

V. Conclusions and Future Work

A mixed reality wheelchair training environment was developed using the Microsoft Hololens. A validation study was carried out based on the methodology that we used in our previous work [4]. Participants received a single short period of training. In the previous experiment, the VR trained group did achieve a statistically significant improvement for some of the manoeuvres carried out on the obstacle course. These results were not repeated here but we still got indications that the VR group showed more improvement in the reverse parking manoeuvre. What we were interested in with this study, however, is whether the MR group performed at least as well as the VR group, and any better than the Control group. No statistically significant results were obtained and so we can conclude that the performance of the MR group does not worsen compared with the other two groups. There is also a strong indicator that the MR group showed more improvement on the slalom task. We believe that a training programme based on repeated use of Wheelchair-MR over an extended period of time would produce a statistically significant improvement, and this is one of the areas that we will investigate in the future.

Results from the SSQs indicated that, even though the technology has improved, using virtual reality still causes cybersickness when there is a mismatch between physical and virtual motion. Using mixed reality instead of virtual reality is one way to negate this issue as the user can see the virtual obstacles within the real world whilst physically moving around. This removes the neuro-conflict that causes cybersickness, although some effects are still present such as eye strain and general discomfort from wearing the device.

Comments were made about different aspects of the training and the application. For example, several participants commented on how small the field of view of the Hololens was and how that made using the application more difficult because they could not see objects in their peripheral vision, making it harder to avoid multiple objects at the same time. Other comments about the virtual objects shifting their position mid-training was also made. This bug was primarily due to the device getting confused as to its location within the very large training area being used.

With the continued development of MR devices and the release of the Magic Leap headset and the second generation of the Hololens, the issues that arose from using MR in this application could potentially be overcome, for example providing a much larger field of view or better tracking in large areas. When the virtual objects can be more seamlessly integrated into the real world then the training value that can be obtained from using the MR hardware would potentially increase.

In the future, we will continue to improve Wheelchair-MR. A particular goal is to allow users to experience familiar rooms (perhaps their own lounge or bedroom) in the environment and be able to practice manoeuvring their wheelchair in the virtual recreation of that space.

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